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*ASP Conference Series, Vol. **VOLUME**, © **YEAR OF PUBLICATION***

****NAMES OF EDITORS****

The Void Phenomenon Revisited

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Abstract. The Void Phenomenon consists in the apparent discrepancy between the number of observed dwarf halos in cosmic voids and that expected from CDM simulations. We approach the problem considering the challenging prospects of detecting field dwarf systems with halo masses $\leq 10^9 M_\odot$, via their possible HI emission. A brief review of recent work is followed by preliminary results from the ALFALFA survey, which suggest the possibility, but not yet the proof, that such objects may have been already detected towards the outskirts of the Local Group.

1 The Void Problem: Where are the Dwarfs?

More than 30 years ago it started to become apparent that bright galaxies are generally found in dense environments and that the vast majority of cosmic space is devoid of them. The high density regions are highlighted by clusters, arising in filamentary structures; regions between them that are underdense in galaxies brighter than $\sim L^*$ by an order of magnitude or more fit spherical volumes of diameter often exceeding 10–20 Mpc, the “voids”. This topology is now well understood as a natural evolution of matter density fluctuations progressively amplified by gravitational instability. Current computer simulations readily reproduce the main characteristics of the observed topology. Voids are not empty, either in simulations or in deep redshift surveys. Peebles (2001, 2008) has however pointed out that a discrepancy appears to exist between observations and simulations obtained within the standard Cold Dark Matter (CDM) scenario: while a significant population of low mass halos is predicted to exist by simulations, observations have failed to detect faint galaxies in the expected abundance. An extension to voids of the morphology–density relation, seen to be relevant in higher density environments, does not seem to explain the discrepancy, as surveys of low surface brightness (e.g. Thuan, Gott & Schneider 1987) and blue compact dwarf galaxies (e.g. Salzer, Hanson & Gavazzi 1990) replicate the topology of brighter galaxies. Peebles has referred to this as the “Void Phenomenon”, which appears to be of analogous nature to the “missing satellite” problem pointed out by Klypin *et al.* (1999) and Moore *et al.* (1999).

The organizers of this conference have asked me to revisit this issue, possibly with the expectation that the partial results of the currently ongoing ALFALFA HI survey may be able to throw some new light, as that survey is highly sensitive to low mass, gas rich systems. In this report, an overview of key observations and high resolution simulations will be followed by results which do not solve the problem — if indeed a void problem still exists: see the paper by Tinker in these proceedings and Tinker & Conroy (2009) — but may provide interesting

clues on how deep we need to go in order to detect the baryonic counterparts of the halos that fill voids. Throughout this report I use $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 Simulations

In its simulations, the *Mare Nostrum* collaboration has addressed with particular attention the issue of dwarf galaxies in voids. In a pure DM simulation box of 115 Mpc size, Gottlöber *et al.* (2003) find that the 20 largest voids have radii larger than 25 Mpc, as traced by $1.4 \times 10^{12} M_\odot$ halos; when halos one order of magnitude smaller are used, the same voids are only 7% smaller in linear size. The mean density within the volume of those voids is about 10% of the cosmic density. Inside the voids, the same topology is found as on larger scales in the Universe: empty regions, filaments and larger concentrations, but with masses scaled down by orders of magnitude. If halo masses of $\sim 10^9 M_\odot$ or smaller are used to trace the topology, the voids are readily filled. Thus, the drop in the number density at the edge of voids is quite steep for large halo masses and imperceptible for small ones. This translates in a difference of an order of magnitude between the halo mass function of the general field and that of large voids, at $10^{11} M_\odot$; yet the two mass functions converge for $10^9 M_\odot$. Hence Peebles' query: where are the real world dwarfs?

Part of the answer is in Hoeft *et al.* (2006), who extended the earlier *Mare Nostrum* simulations with the inclusion of hydrodynamics and of a UV ionizing background. Their most important result is illustrated in Figure 1, which shows the baryon fraction in halos of different masses, in various simulations of high resolution. While halos more massive than about $10^{10} M_\odot$ are able to retain all their baryons, in those smaller than a few $10^9 M_\odot$ most baryons are heated by the intergalactic UV photons and lost by evaporation. While Hoeft *et al.* warn on the possible inadequacies of their radiative transfer treatment, and while the relative absence of giant galaxies in voids attenuates the UV radiation flux, it is clear that the impact of the latter and of other feedback processes on the ability of small halos to retain their baryons can be very important. More recently, Ricotti (2009) has suggested that, as the Universe expands, variations in the Jeans mass in the IGM and increasing concentration of the halos can reactivate gas accretion at late z , increase the minihalos' baryon fraction and stimulate late minibursts of star forming activity.

A further source of uncertainty applies to the results of simulations, especially those that adopt the so-called Halo Occupation Distribution (HOD) paradigm in populating DM halos with baryons and inferring simulated galaxy properties. According to Tinker & Conroy (2009), “the simple proposition within our implementation of the HOD is that galaxy properties are determined solely by the mass of the halo in which the galaxy resides, independent of the halo's larger scale environment”. A number of authors have argued that an “assembly bias” exists, i.e. that the properties of DM halos and the galaxies embedded in them may depend not only on their mass but also on their formation history, which is affected by the environment (e.g. Gao, Springel & White 2005; Wechsler *et al.* 2006), and that such bias may be stronger in lower mass halos. This issue remains unclear; see Tinker's paper in these proceedings.

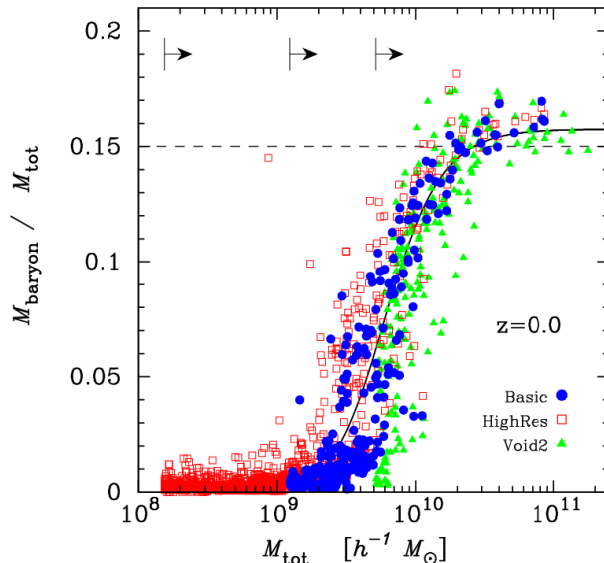


Figure 1. Baryon fraction as a function of halo mass. Simulations by Hoesft *et al.* (2006) of different resolution: lowest are filled circles, highest are unfilled squares. The cosmic baryon fraction is 0.16. Included with permission from M. Hoesft and the Royal Astronomical Society.

3 Observations

Adopting Mathis & White (2001) conversion from halo mass to blue luminosity — with mild extrapolation —, galaxies inhabiting halos of mass $10^9 M_\odot$ and lower would typically be fainter than about -15 . Hoesft *et al.* have however shown that the halo mass function cannot be translated into a luminosity function without full consideration of hydro, radiative transfer and feedback effects: fainter magnitudes than -15 are obtained for void dwarfs if the baryon fractions predicted by Hoesft *et al.* simulations are converted via even generous baryon mass-to-light ratios. Such luminosities are not effectively sampled through the nearest 100 Mpc by current redshift surveys.

In a detailed study, Hoyle *et al.* (2005) extracted two very rich samples of galaxies from the SDSS — “distant” and “nearby”; each sample was divided into two density regimes: “void” and “wall”, via a nearest neighbor algorithm. Galaxies in the distant sample peak at $M_r \simeq -19.5$ and extend to $M_r \simeq -17.5$; the nearby sample peaks at $M_r \simeq -16.5$ and extends to $M_r \simeq -14.0$. The luminosity functions of the void and wall populations differ in Φ^* by a factor of 7 and in M^* by 0.9 mag, yet they have similar faint end slopes ($\alpha \simeq 1.19$). The galaxies in the void sample have halo masses $> 10^9 M_\odot$ and reside near the inner edges of voids. These results are in agreement with the expectations of simulations.

Because field dwarf galaxies tend to be gas rich, with M_{HI}/L typically increasing with decreasing luminosity L , HI searches for gas rich dwarf halo dwellers have been carried out. Besides the challenging demands of such experiments in terms of sensitivity and sky coverage, a most important one is spectral

resolution. A $10^9 M_\odot$ halo translates into a circular velocity of less than 20 km s^{-1} , thus spectral resolutions of 10 km s^{-1} or better are needed in order to prevent signal dilution and allow reliable detection. One of the most extensive HI searches, by Szomoru *et al.* (1996), covered $\sim 1\%$ of the Bootes void. Its spectral resolution, however, was $\sim 45 \text{ km s}^{-1}$, allowing detection of gas only in halos significantly more massive than $10^{10} M_\odot$. This result and those of other surveys have shown that such objects trace voids in a similar manner as more massive ones, but little about the extreme dwarf population.

The Arecibo Legacy ALFALFA extragalactic HI survey (Giovannelli *et al.* 2005), currently under way, aims to cover 7000 square degrees of sky, with a spectral resolution of 5.5 km s^{-1} . As of Spring 2009, about 25% of the survey data are fully processed. The survey sensitivity allows detection of HI masses greater than $M_{\text{HI}} \geq 10^8 M_\odot$ at distances $d > 40 \text{ Mpc}$, $2 \times 10^7 M_\odot$ at the distance of the Virgo Cluster (16.5 Mpc) and $\sim 10^5 M_\odot$ within the Local Group. Preliminary findings of Amelie Saintonge *et al.* (2009), obtained from a 900 square degree contiguous region fully sampled by ALFALFA, near the North Galactic Pole: $09^h < RA < 16^h$, $4^\circ < Dec < 16^\circ$, are shown in Fig. 2. The mean distance of HI detections to the third nearest galaxy brighter than $M_r = -17.9$ is seen to change with M_{HI} : sources with $M_{\text{HI}} < 10^{8.5} M_\odot$ inhabit environments less dense by about a factor of 3 than the more massive HI systems. This result confirms the report of Basilakos *et al.* (2007), based on much poorer statistical grounds using data from the HIPASS survey. Completion of the ALFALFA survey will permit extension of this result much further, both in distance and in mass regime, than evidenced by Figure 2. In addition, over a solid angle of $\simeq 500$ square degrees containing part of the volume of the giant void in the foreground of the Pisces–Perseus supercluster, Saintonge *et al.* find that ALFALFA detects about a dozen HI sources with HI masses $> 10^8 M_\odot$, 4 of which are optically brighter than -18. This is consistent with expectations from simulations. As argued in the next section, the sensitivity of ALFALFA may not be sufficient to detect the possible cold baryonic counterpart of void dwarf halos with $< 10^9 M_\odot$ at distances of tens of Mpc, but it can allow testing the existence of such systems at smaller distances.

4 Are the Low Mass Halos Detectable?

According to Fig. 1, a halo of $10^9 M_\odot$ can retain a baryon mass of at most a few $10^7 M_\odot$. Wide field optical surveys such as 2MASS and SDSS have been quite effective in discovering a significant number of dwarf satellites of the Milky Way. Their kinematics indicate total masses within a 300 pc radius on order of $2 \times 10^7 M_\odot$, with $M/L > 100$ and $10^3 < L < 10^5 L_\odot$ (Strigari *et al.* 2008). These faint, often tidally disrupted dwarf spheroidal systems are very nearby, largely within the virial radius of the MW itself and the total halo masses of their precursors are difficult to estimate. Their discovery is helping to alleviate the “missing satellite” problem. However, morphological segregation suggests that the typical field dwarf is more likely to be a gas rich, irregular system. This idea has been applied by Blitz *et al.* (1999) and Braun & Burton (1999) to a category of objects that has been known for decades: HI high velocity clouds (HVCs). They proposed that HVCs could be gas rich, optically impaired

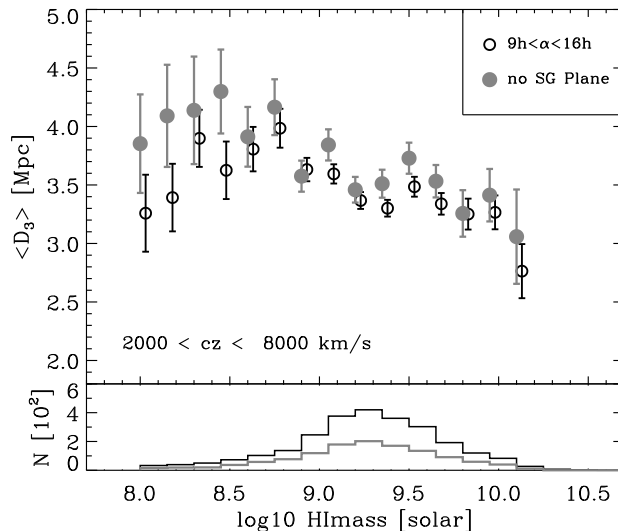


Figure 2. Distance to the third nearest neighbor brighter than $M_r = -17.9$ (completeness limit 17.5 at $cz=8000 \text{ km s}^{-1}$) vs. the HI mass in a preliminary subset of the ALFALFA HI survey. This subset covers 900 contiguous square degrees (13% of the projected survey coverage) between 09^h and 16^h , 4° and 16° . Filled symbols refer to a subsample which excludes objects in the Supergalactic plane (Saintonge *et al.* 2009).

halos, spread over the Local Group. In that scenario, the so-called “compact” HVCs would be the relatively undisturbed systems, while the very extended HVC complexes would be the tidally disturbed remnants of ongoing infall to the Galactic disk. Catalogs of compact HVCs have been produced (e.g. de Heij *et al.* 2002; Putman *et al.* 2002) and their global kinematics carefully investigated. The typical dwarf halo associated with a compact HVC in this scenario would have an observed HI mass of $10^7 M_\odot$, a linear size of 3-10 kpc and a total mass in excess of $10^8 M_\odot$. The main objections to this idea arise from both observations and theory. Observationally, systems with $M_{HI} \simeq 10^7 M_\odot$ should have been detected in nearby groups of galaxies, other than the MW; they have not. From the theory side, Sternberg *et al.* (2002) have shown (i) that most of the gas in a minihalo should be found in a ionized phase, rather than in the form of HI, and (ii) that the linear sizes of the compact HVCs, if located at typical LG distances ($\sim 1 \text{ Mpc}$), are too large and would violate the halo mass-concentration relation. If that violation were ignored, they also argue, the resulting halo models would require a baryon to DM mass fraction greater than the cosmic value of $\simeq 0.16$.

The models of Sternberg *et al.* (2002) provide useful templates for the thermal structure minihalos would be expected to have. For example, a thermally stable dwarf system of halo mass $3 \times 10^8 M_\odot$, embedded in a hot intergalactic medium of pressure $\simeq 10 \text{ cm}^{-3} \text{ K}$, would have a gas mass of $1.8 \times 10^7 M_\odot$, mostly warm ($\simeq 10^4 \text{ K}$) and ionized, envelopping a neutral core of $M_{HI} \simeq 3 \times 10^5 M_\odot$, with a peak column density of $N_{HI} \simeq 4 \times 10^{19} \text{ cm}^{-2}$ and mean radius of the neutral gas $R_{HI} \simeq 0.7d \text{ kpc}$. The detection of such an object at even modest extra-

galactic distance poses a stiff challenge, but it is possible with ALFALFA within distances of 2–3 Mpc. Objects with those characteristics were then searched for in the above-mentioned region near the NGP (Giovanelli *et al.* 2009). At high galactic latitude, intrusion of Galactic HI emission was minimized. About two dozen extremely compact sources were found, with M_{HI} between $5 \times 10^4 d^2$ and $10^6 d^2 M_\odot$, R_{HI} between $0.4d$ and $2.8d$ kpc (several sources are unresolved and smaller than 0.4 kpc), peak column densities of a few 10^{19} cm^{-2} and linewidths near 25 km s^{-1} , with the unknown distance d in Mpc. A number of dwarf galaxies in the Local Group periphery, with redshift independent estimated distances of 2.5 Mpc or less, are found in that region of the sky, including Sex B, GR8, KKH86 and DDO187. The velocity distribution of the newly discovered clouds matches well those of the nearby galaxies in the field. Leo T, a dwarf at a distance of 0.42 Mpc, with $M_{HI} = 3 \times 10^5 M_\odot$ can be said to be very gas-rich, as $M_{HI}/L_V \simeq 5$ (Ryan–Webber *et al.* 2008). With an HI radius $R_{HI} = 0.3$ kpc and an optical counterpart that lies below the threshold of optical surveys, the properties of Leo T are comparable with those of the compact HI clouds discovered by ALFALFA. However, while those properties are consistent with the hypothesis that the new ALFALFA sources are the baryonic counterparts to a population of low mass halos, it is not yet possible to exclude that they may be part of the wider scenario of the (yet relatively poorly understood) perigalactic HVC phenomenon. Completion of the ALFALFA survey will shed more light on this matter. The search for analogs of these sources in nearby groups of galaxies and in the Local (Tully) Void, well outlined by galaxies in the *Catalog of Nearby Galaxies* of Karachentsev *et al.* (2004), is a near term, exciting prospect.

This work was supported by the NSF grant AST-0607007.

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